

Eclipses by a Circumstellar Dust Feature in the Pre-Main Sequence Star KH15D

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ABSTRACT

Photometry and spectroscopy of the unique pre-main sequence eclipsing object KH15D in the young cluster NGC 2264 are presented. The orbital period is 48.34 days and both the length (~ 16 d) and depth (~ 3 mag) of the eclipse have increased with time. A brightening near the time of central eclipse is confirmed in the recent data but at a much smaller amplitude than was originally seen. Spectra taken when the star is bright show that the primary is a weak T Tauri star of spectral type K7. During eclipse there is no detectable change in spectral type or reddening, indicating that the obscuration is caused by rather large dust grains and/or macroscopic objects. Evidently the star is eclipsed by an extended feature in its circumstellar disk orbiting with a semi-major axis of ~ 0.2 AU. Continued photometric monitoring should allow us to probe the disk structure with a spatial resolution of $\sim 3 \times 10^6$ km or better.

Subject headings: stars: pre-main sequence - stars: rotation - open clusters and associations: individual (NGC 2264)

1. Introduction

T Tauri stars are recognized as pre-main sequence (PMS) stars (e.g. Bertout 1989) and exhibit photometric variability. Their light variations are believed to arise primarily from a changing pattern of hot accretion zones and cool spots on their surfaces, but variable extinction caused by circumstellar matter may be involved in some instances (Herbst et al. 1994, Bertout 2000). The presence of circumstellar disks around PMS stars has been inferred since the late 1960s. Shu, Adams, and Lizano (1987) proposed the penultimate evolutionary stage of low-mass star formation as a T Tauri star with a surrounding remnant

nebular disk. The disappearance of the nebular disk occurs as matter accretes onto the star, becomes incorporated into planets or stellar companions, or is dispersed by an energetic outflow. Circumstellar disks have now been directly imaged by the Hubble Space Telescope (O’Dell & Wen 1994, O’Dell & Wong 1996). With recent detections of Jupiter-sized planets orbiting main-sequence stars at distances of 0.2 - 3 AU (Marcy & Butler 2000), the question remains: how do disks surrounding young stellar objects evolve and, in particular, what is the time scale for planet formation? Direct observation of circumstellar disk structure could place strong constraints on the nature of physical processes occurring in protoplanetary disks but most PMS stars are too distant to allow much resolution of their disks with current imaging capabilities.

During a photometric study of the young cluster NGC 2264, Kearns & Herbst (1998; hereafter KH) discovered a unique and potentially important object, which we call KH15D, following their designation. It is a periodic variable ($P \sim 48$ days) that appears to undergo a regular eclipse, but with an amplitude of 3 to 4 magnitudes in the Cousins I band. Amazingly, the duration of the eclipse is about one-third of the period, or 16 days. The star has now been observed photometrically through dozens of cycles and its period and phase are well known and predictable, indicating that we are dealing with an orbital phenomenon. The depth of the eclipse, its duration, and the evidence for photometric variability during totality all indicate that the eclipsing object is not a normal star. Here we present and discuss evidence that KH15D is being eclipsed by a feature in its circumstellar disk, and describe the constraints our data place on the nature of that feature.

2. Observations

2.1. Photometry

Photometry of KH15D was obtained during six observing seasons from 1995 October through 2001 April with the 0.6 m Perkin telescope of the Van Vleck Observatory on the campus of Wesleyan University. A Cousins *I* filter was used for all observations and exposure times were 5 minutes. The scale of the images is 0.6'' per pixel and typical seeing was about 2.5''. Flat-fielding was accomplished with sky flats and the images were also corrected for bias and dark noise. Aperture photometry was performed using standard IRAF³ tasks and an aperture diameter of 4.8''. Differential magnitudes were determined by reference to a set of comparison stars on the same frame. Typical errors are ~ 0.01 mag when the star is in its bright state and ~ 0.1 -0.2 mag when in eclipse. Portions of frames showing KH15D in and out of eclipse are shown in Fig. 1 to identify the star and to illustrate its extraordinary range.

A periodogram analysis of the full data set indicates that the star's period is 48.35 d, consistent with the value of 48-49 d reported by KH based on two seasons of data. This was modified slightly, to $48.34 \text{ d} \pm 0.02$ (estimated error) by inspection of the folded light curves. Phased light curves at three epochs of observation are shown in Figure 2. It is evident that the shape of the light curve has evolved substantially over the five year interval represented by the data. In particular, the central brightening in the first two epochs appears to be significantly brighter than the out-of-eclipse levels at those epochs. In 95-96,

³Image Reduction and Analysis Facility, written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation.

the magnitude of this effect is ~ 0.5 mag and in 96-97 it is ~ 0.1 mag. By 99-00 however, the central reversal has diminished dramatically and is well below the out-of-eclipse level for that year. There may also be a slight lengthening of the eclipse duration between 96-97 and 99-00 of about 0.02 in phase (~ 1 day) but it is difficult to be certain given the gaps in the light curve. We are perhaps seeing the evolution of a feature driven by orbital dynamics, although the source of the dramatic central brightness elevation in 95-96 remains mysterious. An ephemeris for mid-eclipse based on these data is

$$JD(\text{mid} - \text{eclipse}) = 2451626.86 + 48.34E.$$

Out of eclipse the star appears to be of constant brightness to within ± 0.03 mag.

2.2. Spectroscopy

Moderate resolution spectra ($\Delta\lambda \sim 4$ Å) of KH15D were obtained on the nights of 15, 16, and 17 December 2000 when it was in its bright state (phase = 0.56) and again on 14 January 2001 during an eclipse (phase = 0.15). The data were collected using the B and C spectrograph plus the Loral 800 x 1200 CCD detector on Steward Observatory's 2.3 meter telescope through light, variable cirrus clouds. These moderate resolution spectra were taken using the 600 lines per mm grating blazed at 6681 Å, covering the wavelength range $\sim 4860 - 7000$ Å, at a dispersion of 1.83 Å/pixel. The L42 filter was used to block light with wavelengths shorter than 4200 Å. The images were processed using standard IRAF tasks. This included bias subtraction and flat field corrections using a quartz lamp. All frames were found to have a slight gradient present along the slit. In order to remove this, an illumination correction was performed. Dome flats were used to determine the slit illumination function. This was accomplished with the task ILLUM in IRAF. One-dimensional spectra were then extracted using the APALL task, and wavelength calibration was established from exposures of a He-Ar comparison lamp taken

immediately following each program star exposure. Lastly, all spectra were flux calibrated using the standard star G191b2b and the usual IRAF tasks (STANDARD, SENSFUNC, CALIBRATE).

Figure 3 shows our reduced spectra for KH15D in and out of eclipse. The spectrum in the top panel is a 1 hr exposure of the star in its bright state. The spectrum in the bottom panel is an average of six one hour exposures obtained during eclipse. We multiplied this spectrum by 14.7 so that both spectra could appear on the same scale. Locations where a bad background and night sky subtraction could not be avoided are marked. These are labeled as BGS and NS respectively. Atmospheric absorption bands are identified by ATM. Direct comparison of the spectrum in the bright phase was made with standard star spectra obtained using the same telescope and instrument at a lower resolution for classification purposes. Careful inspection of the spectra in both panels shows that they are nearly identical, and that they both exhibit stellar features indicative of a K7 V spectral type. In particular, the presence and strength of the TiO features, in addition to the MgH feature, is clear evidence of a late K star. Other lines used for classification purposes were chosen from the list given by Cohen & Kuhi (1979) and are labeled in the plot. The presence of the $\lambda 6707$ Li I feature and the lack of any substantial H α emission indicate that this is a weak-lined T Tauri star (WTTS) and confirms the youthfulness of this system. During the bright phase, the Li feature has an equivalent width of 0.469 \AA , consistent with the Li equivalent widths measured for stars in NGC 2264 by Soderblom et al. (1999). It should be noted that due to the low resolution of our spectra, the Li feature is blended with the Fe I line at 6707.441 \AA , and therefore our measured value should be taken as an upper limit. A cross-correlation of the spectrum in eclipse with the spectrum out of eclipse was performed using the FXCOR task in IRAF in an effort to determine a radial velocity. The spectra were not sufficiently resolved, however, to deduce a reliable relative radial velocity.

2.3. Properties of the Star

Table 1 lists the known and inferred properties of KH15D. Photometry presented has been obtained by two different groups. We used Park et al.’s (2000) distance to NGC 2264, and their values of V and B-V, to determine the absolute magnitude of KH15D. A value of M_{bol} was then obtained by applying the bolometric correction used by Hillenbrand (1997) for stars with $3.826 \geq \log T_{eff} \geq 3.571$. Adopting $M_{bol,\odot} = 4.74$ (Bessel et al. 1998), a luminosity and radius for this star was calculated. We then used evolutionary tracks and isochrones from D’Antona & Mazzitelli (1994, 1998), and Baraffe et al. (1998) to obtain estimates for the mass and age of KH15D. Out of eclipse, the star appears to be an ordinary WTTS member of the young cluster NGC 2264 with a mass of $\sim 0.5\text{--}1.0 M_{\odot}$ and an age of $\sim 2\text{--}10$ My. The large range in these values reflects the scatter in the models used. In summary, KH15D appears to be a normal PMS star. We suppose that what is unusual about this star is that it has a fortuitous alignment of its circumstellar disk with our line of sight such that an orbiting feature in the disk periodically occults the star.

3. Discussion

KH15D exhibits unique photometric behavior, to the authors’ knowledge. The strict periodicity, large amplitude and shape of the light curve make it certain, in our view, that we are witnessing the eclipse of a star by an orbiting extended body (or “feature”). Since we were unable to determine accurate radial velocities of the star from our spectra, we do not yet know for certain whether the K7 star is the more massive object, but that seems likely for the following reason. If the unseen object were more massive, and the visible star were being occulted by a disk surrounding it, that disk would need to extend nearly the entire distance between the components to account for the observed length of the eclipse ($\sim 1/3$ of the orbital period), assuming a circular orbit. This is certainly not a

dynamically stable arrangement. Circumstellar disks in a binary system are limited to radii of $\sim 0.2\text{--}0.5a$, where a is the closest approach of the components (Mathieu et al. 2000). Assuming a circular orbit, this would limit the length of an eclipse in such a system to ≤ 7 d, much shorter than observed. Also, we note that there is no evidence of a second source of light in the system, as might be expected if the unseen feature were more massive than the K7 star. Therefore, we expect that radial velocity data will show little or no orbital motion for the K7 star, although this clearly needs to be checked. Very high precision data might ultimately reveal the mass of an unseen component, if it is comparable to that of a giant planet.

Assuming, therefore, that the occulting body is of relatively low mass and orbiting the K7 star, and adopting the properties of the system given in Table 1, we find that the semi-major axis of the orbit is 0.2 AU, or about 22 stellar radii and that the feature extends over about 1/3 of the circumference of the orbit, assuming it is not highly eccentric. Clearly it must consist of a myriad of smaller objects that are larger than interstellar dust grains (since no reddening is associated with the obscuration) but still have substantial surface area for their mass (to produce the required extinction). The amazing reversals seen in the 1995-1996 and 1996-1997 seasons, when the star exceeded its usual bright state, indicate that there are substantial density fluctuations within this obscuring cloud and, sometimes, holes. The leading and trailing edges seem to be fairly sharply defined. A knife edge occulting the star would lead to an ingress and egress rate of about 0.27 mag/hr, which would last about 0.45 day. These values are consistent with what we actually observe and indicate, therefore that the edge of the occulting feature is rather sharp.

In summary, KH15D appears to be a 2-10 Myr old, $0.5\text{--}1.0 M_{\odot}$ star orbited and periodically occulted by an extended dust feature at a distance of about 0.2 AU. The dust feature is obviously asymmetric, structured and evolving on timescales of months to years.

It extends $\sim 120^\circ$ and could be a “ring arc” similar to what is seen in Neptune or a portion of a warped disk that extends vertically into the line of sight only at certain longitudes. Perhaps it has its origin in the interplay of the star’s magnetic field with the disk, analogous to what has been proposed for AA Tau by Terquem & Papaloizou (2000). However, this feature is much farther out from the star than in that case, applies to a weak T Tauri star, in which the gaseous disk is likely to be already absent, and the star has no evidence of a particularly strong, well-aligned magnetic field (i.e., no spot variations outside of eclipse). Therefore, we consider it more probable that the source of the warp or asymmetry in the disk is gravitational in nature. It is, perhaps, of note that the onset of the feature is at $\pm 60^\circ$ relative to the center of the feature, namely at the Lagrangian points of the orbit of a putative central body. The vertical extent of the feature at its center must be comparable to or larger than the star, of course, since there is nearly complete blocking of the light at the most recent epoch. However, the fact that there is a central reversal of the light to its full (or even somewhat exceeding its full) brightness in the earlier epochs suggests that the scale height may not be much larger than the star. It is probably not warranted to speculate further about this object at present. Clearly, the star deserves special attention because of its potential to yield information on a spatial scale that will not be reached by imaging for many years to come. We are organizing an observing campaign for the upcoming season and would welcome participation by any interested parties.

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Table 1. Relevant Properties of KH15D.

Parameter	Value
Position:	$\alpha = 06:41:10.18, \delta = +09:28:35.5, 2000.0$
Alternate Identifications:	150 ^a ; 391 ^b
Photometry (Out of Eclipse):	$V = 16.096^a, 16.00^b$
...	$U-B = 1.081^a$
...	$B-V = 1.308^a, 1.32^{b,c}$
...	$V-I = 1.571^a$
...	$V-R = 0.82^b$
...	$R-I = 0.80^b$
Eclipse Depth:	3 mag in I
Eclipse Ephemeris:	$JD(mid - eclipse) = 2451626.86 + 48.34E$
Spectral Type:	K7 V
$W_\lambda(\text{Li})$:	0.469 Å
$\log T_{eff}$:	3.61 ^b , 3.602 ^d
Reddening, Extinction:	0, 0
Bolometric Correction:	-0.97 ^e
Distance:	760 pc ^a ; 760 pc ^f
Luminosity:	0.5 (L_\odot) ^b ; 0.4 (L_\odot)
Radius:	1.3 (R_\odot)
Mass:	0.6 (M_\odot) ^b ; 0.5-1.0 (M_\odot) ^g
Age:	2 Myr ^b ; 2-10 Myr ^h

^aPark et al. 2000

^bFlaccomio et al. 1999

^cThe B-V value originally quoted in Flaccomio et al. 1999 was 0.32. Since this is grossly different from what is expected for this star, we assumed that the value was supposed to be 1.32.

^dValue obtained from Cohen & Kuhi 1979.

^eHillenbrand 1997

^fSung et al. 1997

^gValues obtained using evolutionary tracks based on PMS evolution models from D’Antona & Mazzitelli (1994, 1998) and Baraffe et al. (1998).

^hValues obtained using evolutionary tracks based on PMS evolution models from D’Antona & Mazzitelli (1994, 1998) and Baraffe et al. (1998).

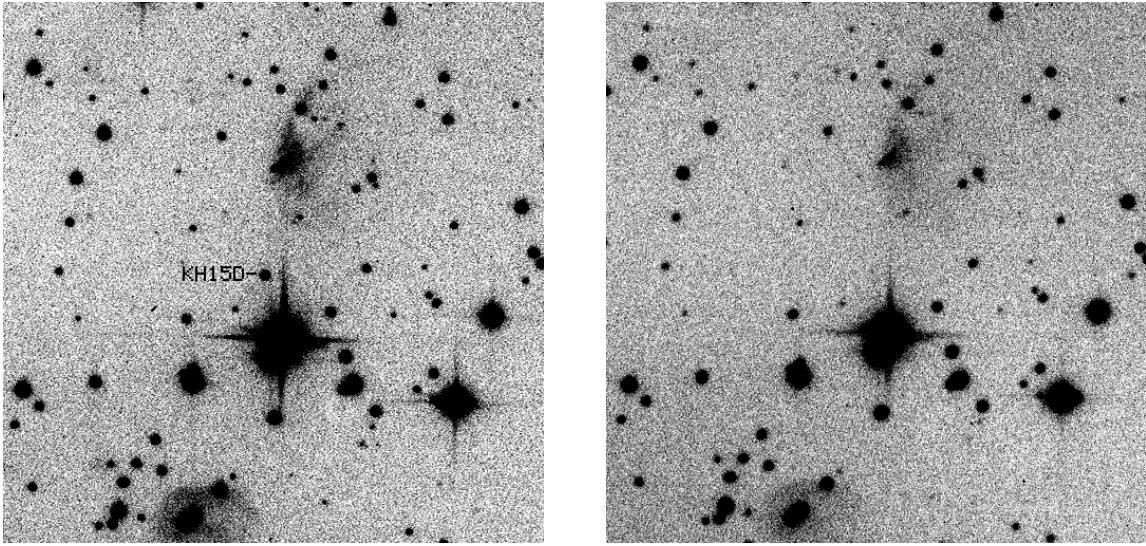


Fig. 1.— Images of KH15D in and out of eclipse obtained through a Cousins I filter with the 0.6 m telescope at Van Vleck Obs. North is at the top and east to the left and the frames are $\sim 5'$ on a side.

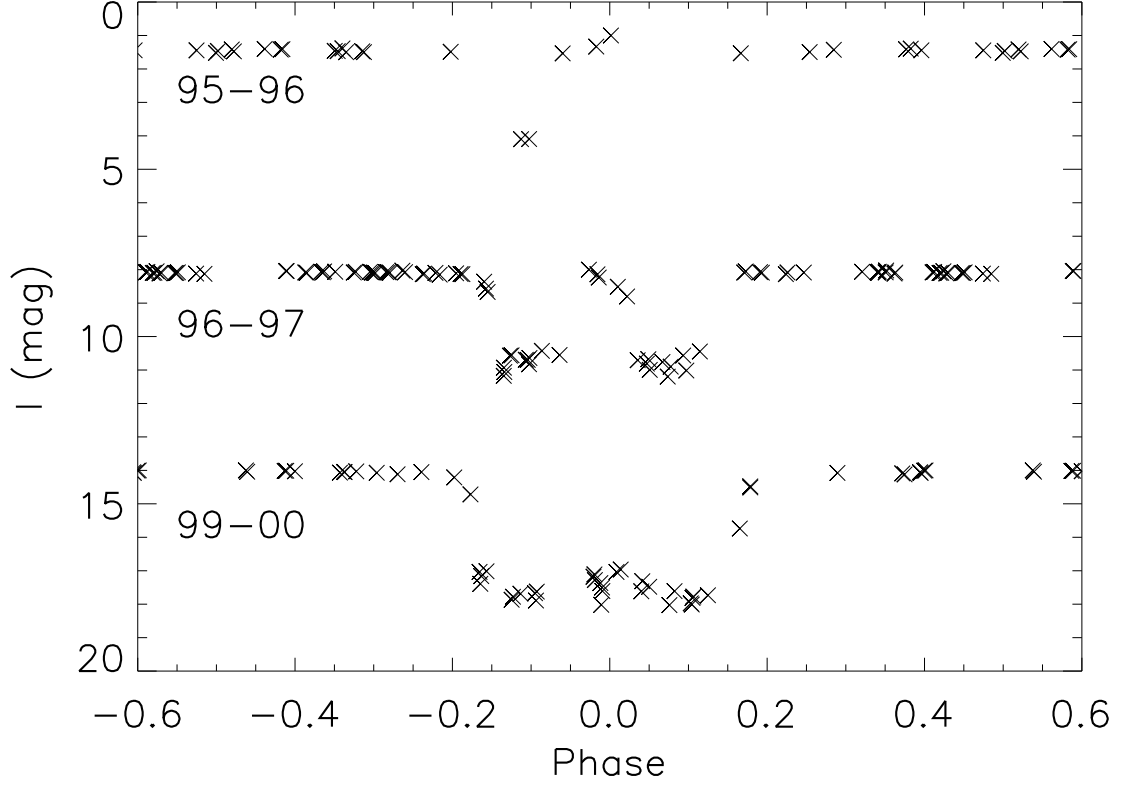


Fig. 2.— Light curves of KH15D during three different observing seasons. All data were obtained with the 0.6 m telescope of Van Vleck Observatory through a Cousins I filter. Differential magnitudes are plotted with arbitrary offsets. It is clear that the width and depth of the eclipse have increased with time and that the brightness of the central peak has markedly decreased.

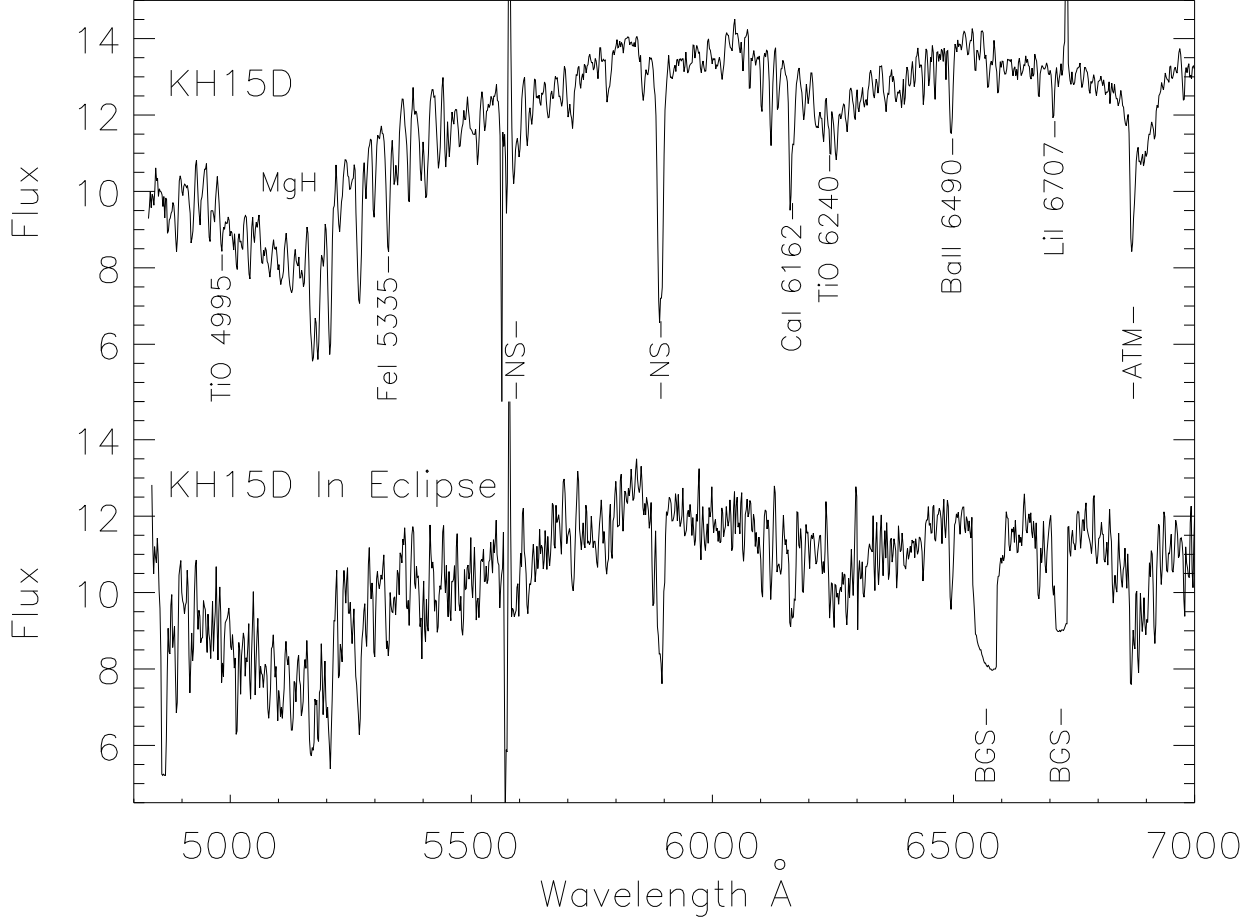


Fig. 3.— A comparison of the spectrum of KH15D in and out of eclipse. The units of flux are 10^{-16} erg cm $^{-2}$ s $^{-1}$. The spectrum in the bottom panel was multiplied by a factor of 14.7 in order to place it on the same scale as the spectrum obtained in the bright phase. Features used in the spectral classification of this object have been labeled. The truncated features marked BGS in the eclipse spectrum at H α and $\lambda 6717$ [S II] are due to poor background subtraction and are not real features. Also note the apparent emission of [S II] in the spectrum during its bright phase. This is also an artifact of the background subtraction. NS and ATM refer to the night sky and atmospheric absorption features.